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Hybrid Chemical-Electric Trajectories for a Mars Sample Return Mission

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Introduction

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Hybrid Chemical-SEP propulsion is well suited to an MSR Earth Return Orbiter.

Chemical Propulsion

- Provides timely Delta V.
- Useful to meet challenging timeline constraints.
- Ex: coordinate with surface mission, save time reaching LMO.

Electric Propulsion

- Provides bulk Delta V.
- Useful to handle high Delta V requirements.
- Ex: Departing LMO and returning to Earth.

ERO has both of these

Introduction

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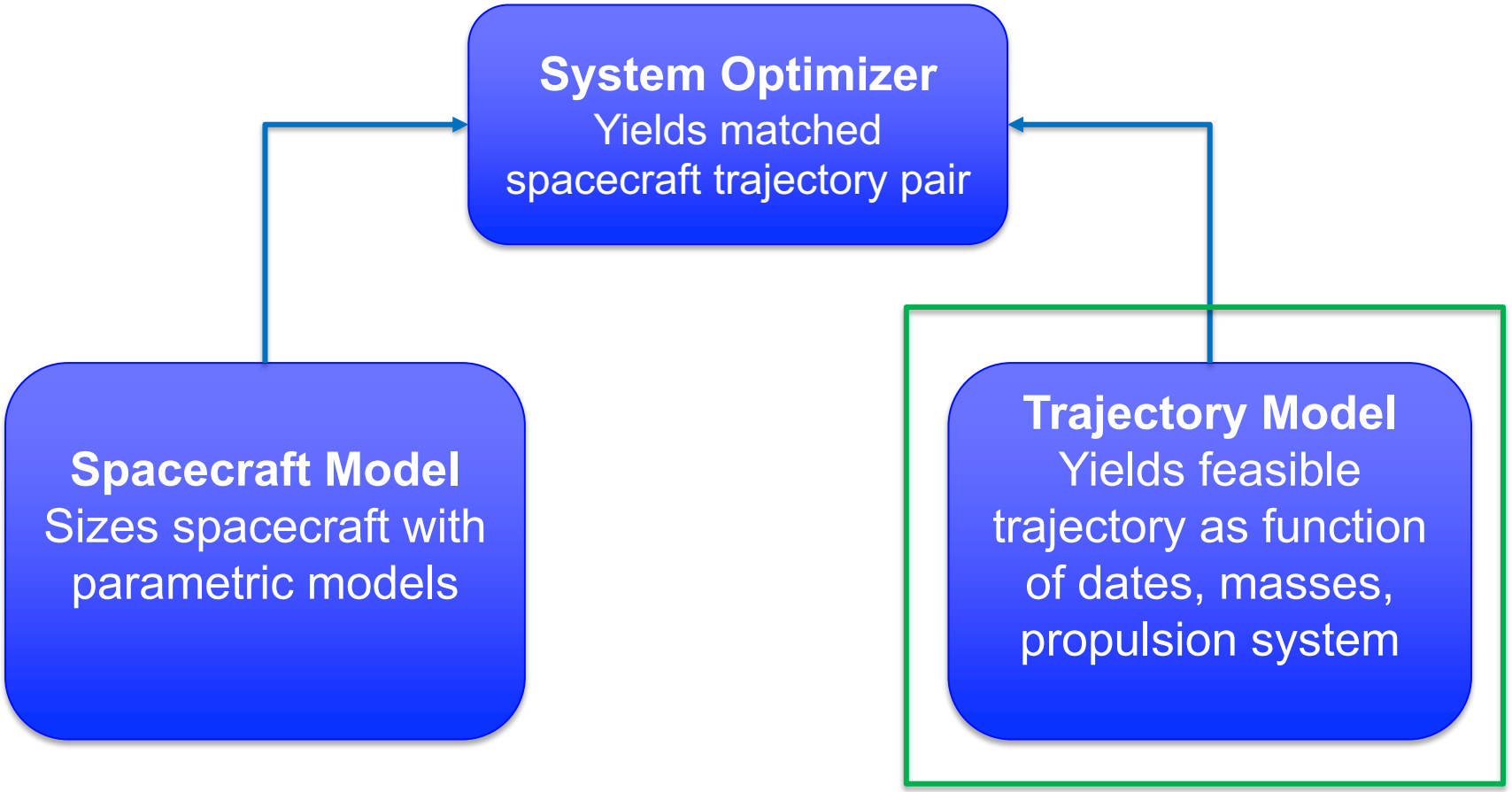
Using SEP means spacecraft and trajectory are coupled.



Trajectory Database

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- A database of low thrust trajectories serves as the trajectory module in the optimization.
- Alternative would be optimizer-in-the-loop.
- Database allows system optimizer to run faster, and provides confidence in solution since we have mapped out entire trajectory design space.

Outbound Grid

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Thrusters: RIT 2X, T6, PPS, Hermes (ARM)

Variable	Lower Bound	Upper Bound	Step Size	# of pts
Power at 1 AU	11 kW	120 kW	Variable	10 per thruster config
Launch Date	March 5, 2025	June 12, 2029	20 days	79
Helio TOF	100 days	1600 days	20 days	76
Arrival Velocity	0 km/s	3 km/s	0.2 km/s	16

~30 million total trajectories

Inbound Grid

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Thrusters: RIT 2X, T6, PPS, Hermes (ARM)

Variable	Lower Bound	Upper Bound	Step Size	# of pts
Power at 1 AU	11 kW	120 kW	Variable	9-11 per thruster config
Launch Date	April 24, 2027	Sep. 19, 2033	20 days	118
Helio TOF	100 days	1600 days	20 days	76
Arrival Velocity	1.5 km/s	6.8 km/s	-	3
Earth Arrival Mass	750 kg	3500 kg	variable	5-10 per thruster config

~70 million total trajectories

Optimizing Outbound Hybrid Trajectory

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Inputs

LEVEL 1

Direction	Opportunity	Starting	End
Earth→Mars	2026	Ariane 64	LMO

LEVEL 2

Thruster	Thruster #	Power
T6	3	30 kW

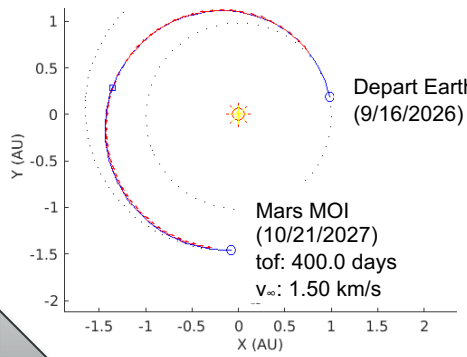
LEVEL 3

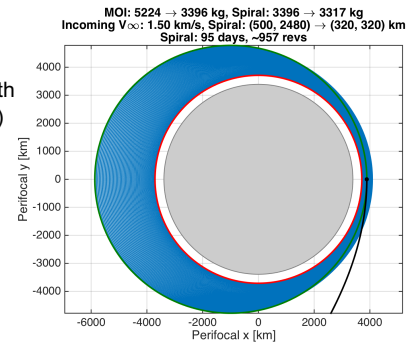
Launch	LMO Arrival
16-Sep-2026	29-Jan-2028

LEVEL 4

Helio TOF	Arr. Vinf
400 day	1.5 km/s

Outputs





Launch Mass	Launch C3	Arrival Mass
5500 kg	5.0	3317 kg

Xenon Used	Key Trajectory Dates
355 kg	

Biprop Used	Optimized Thrust Profile
1828 kg	

Searching for Hybrid Transfer

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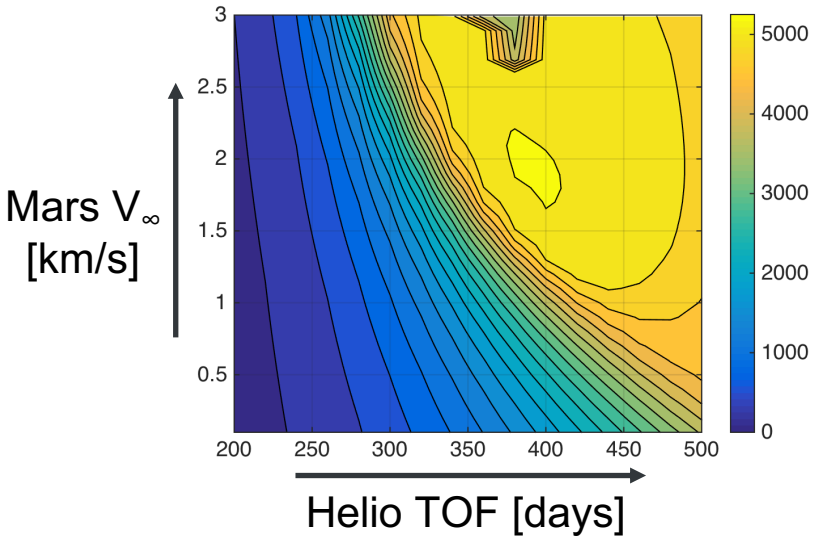
Level 1: E → M, 2026, Ar64 → LMO

Level 2: T6×3, 30 kW

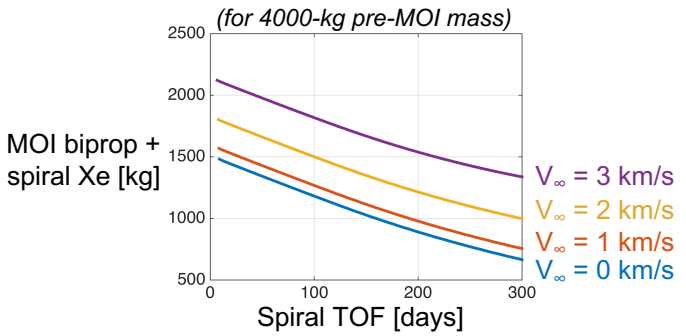
Level 3: Launch Sep. 16, 2026
→ LMO Jan. 29, 2028 (500 days)

Level 4: Heliocentric TOF, Mars V_∞ *(search all combinations for max LMO mass)*

Pre-MOI mass [kg]
(optimal transfer database for launch date)



(for 4000-kg pre-MOI mass)



Pre-MOI mass
Mars V_∞
Spiral TOF
→ Optimal Mars spiral database → LMO mass

Helio + spiral TOF = 500 days

Selecting Hybrid Transfer

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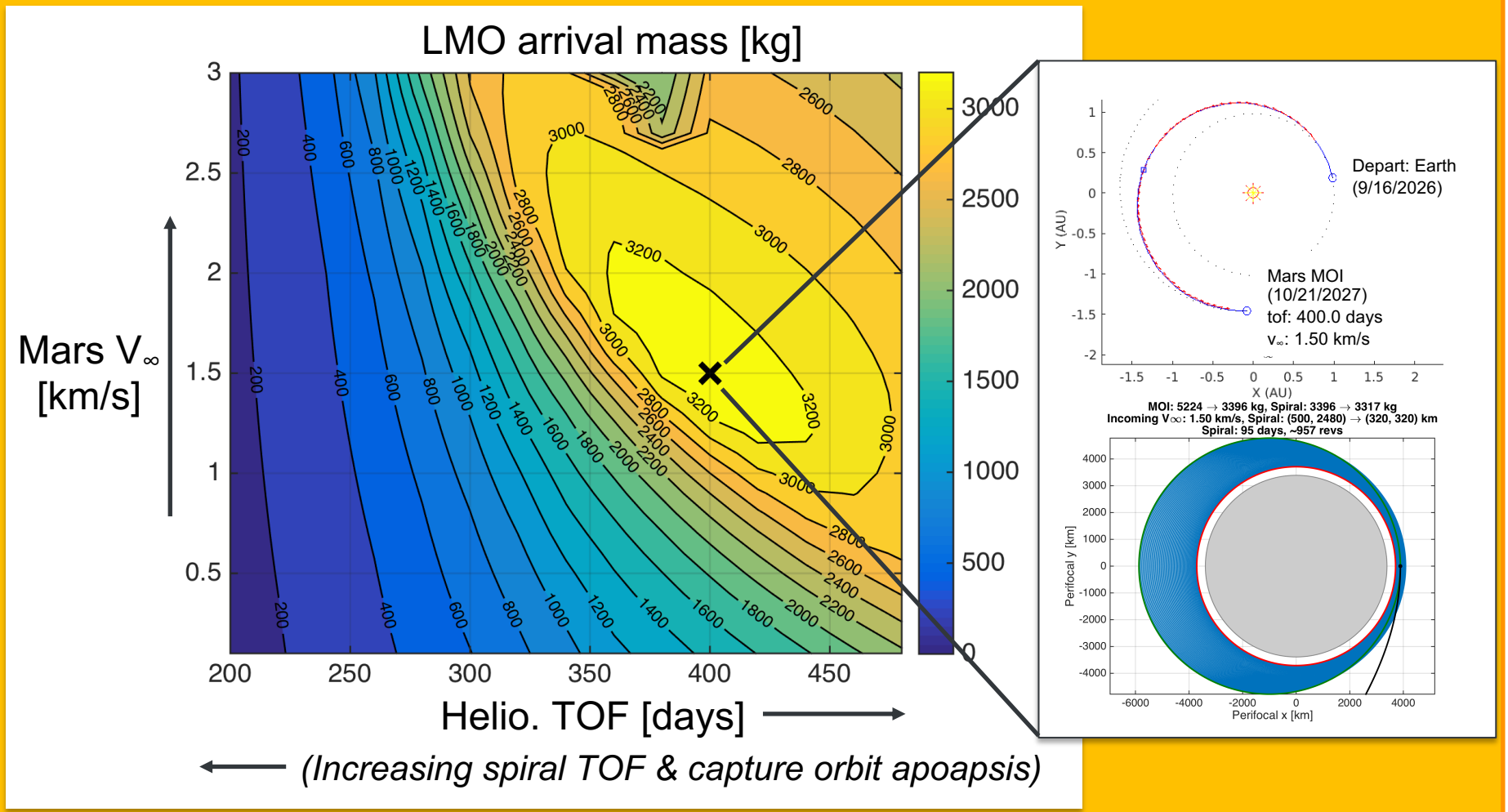
Level 4: Heliocentric TOF, Mars V_∞ *(search all combinations for max LMO mass)*



Creating Hybrid Bacon Plots

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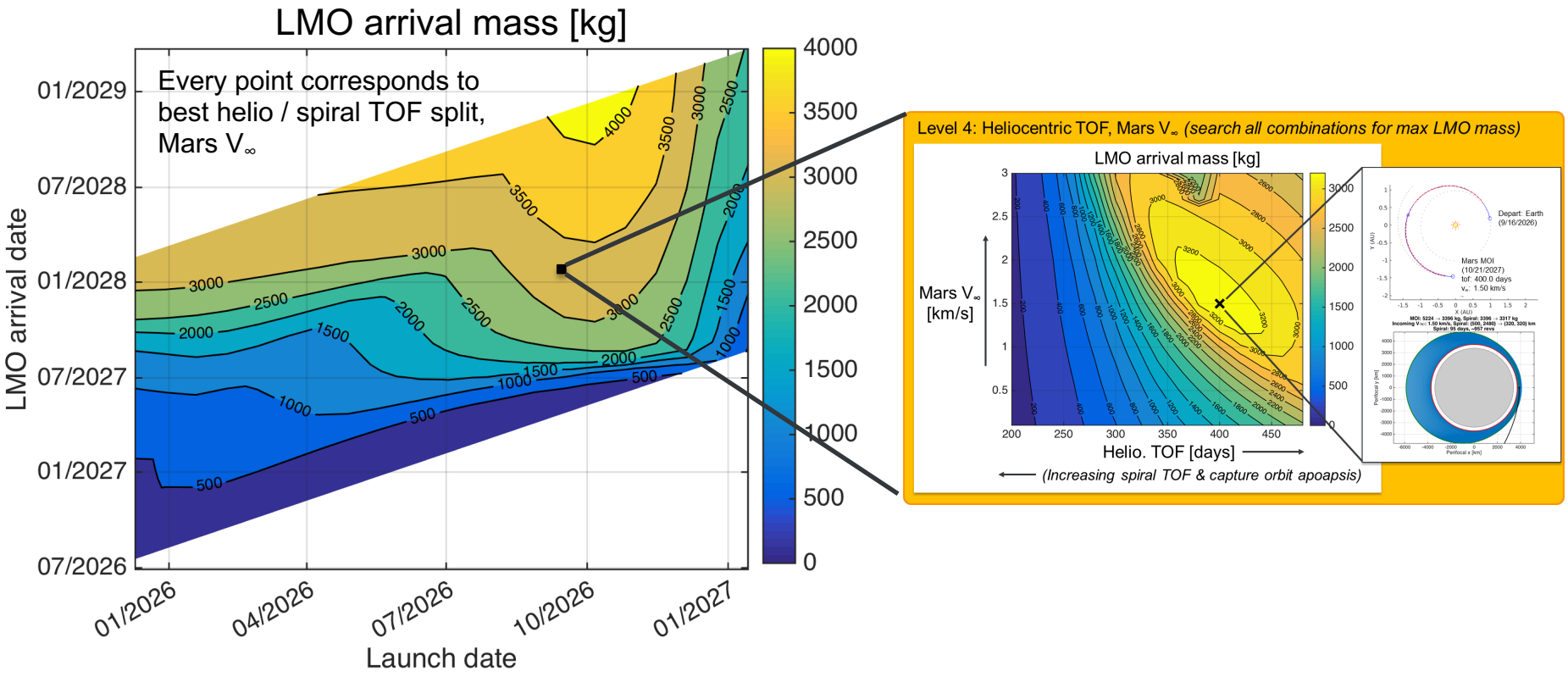
Level 1: E → M, 2026, Ar64 → LMO

Level 2: T6×3, 30 kW

Level 3: Vary launch date → vary LMO arrival date



Mars → Earth Hybrid Bacon Plots

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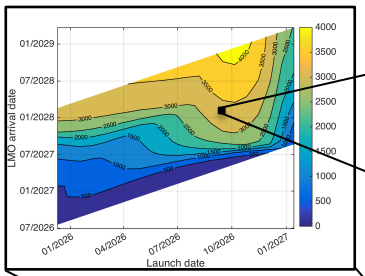
Two New Level 1's:

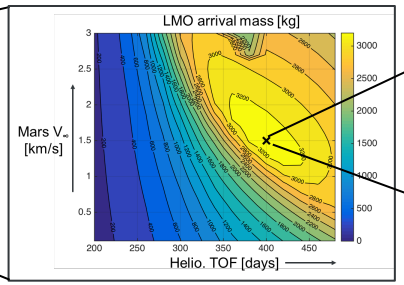
LEVEL 1

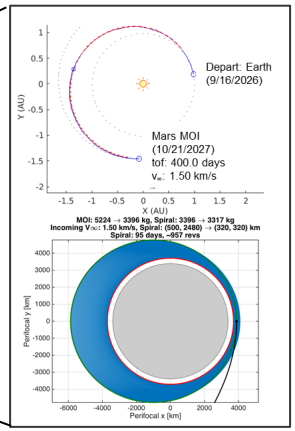
- **Direction**: Mars→Earth
- **Opportunity**: 2028
- **V-infinity**: < 6.5 km/s
- **Starting**: LMO
- **End**: Earth
- **Final Mass**: 1500 kg

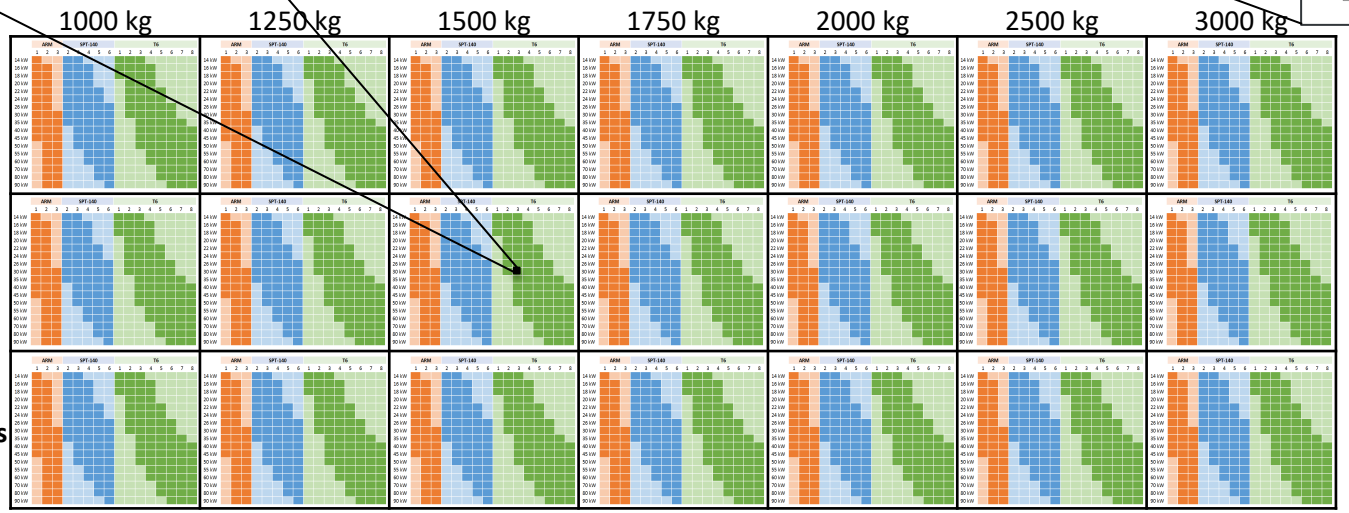
→ **~4000 Complete Bacon Plots**
(26 million trajectories)

(20x the E→M data)









Outbound Example

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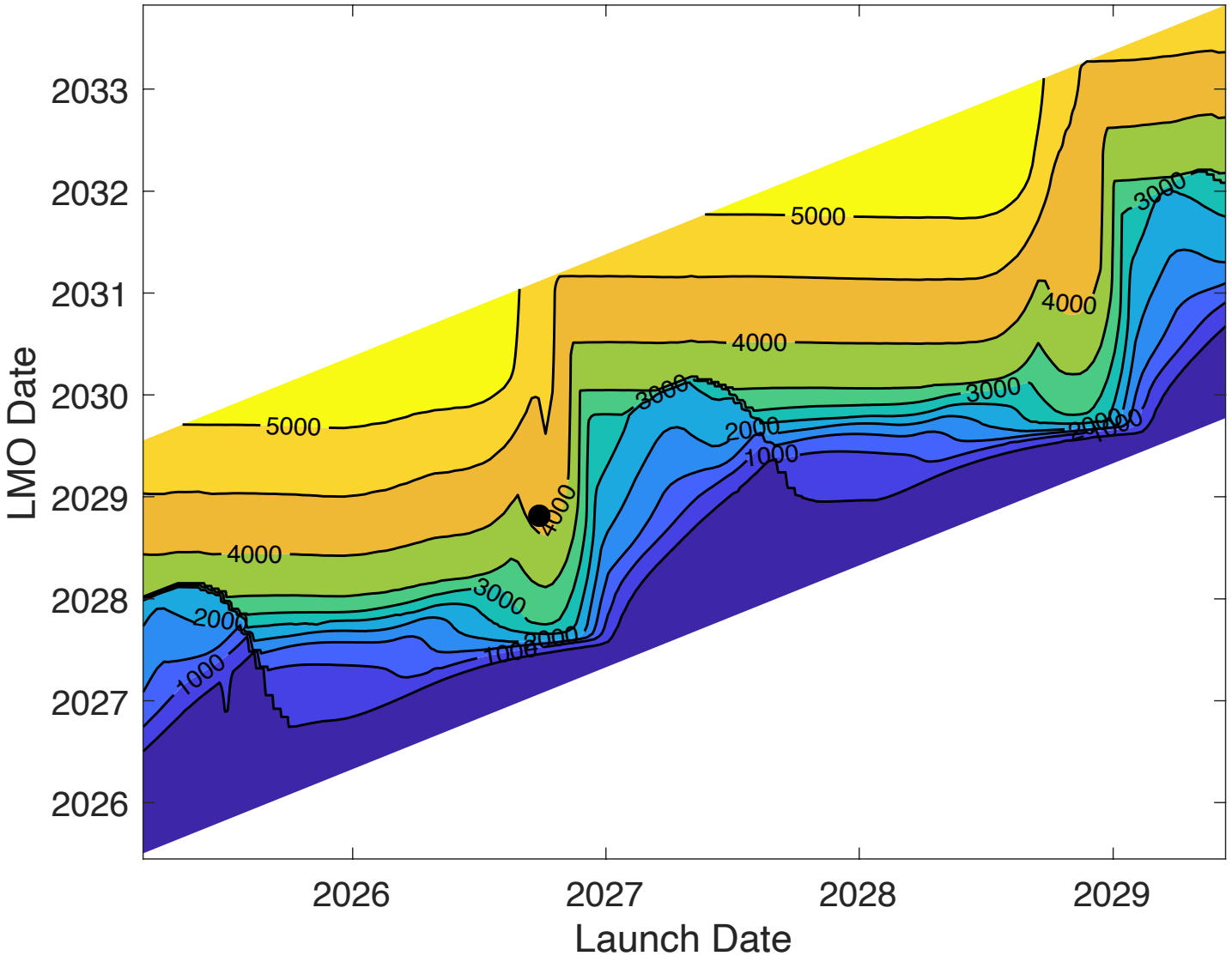

Outbound Example

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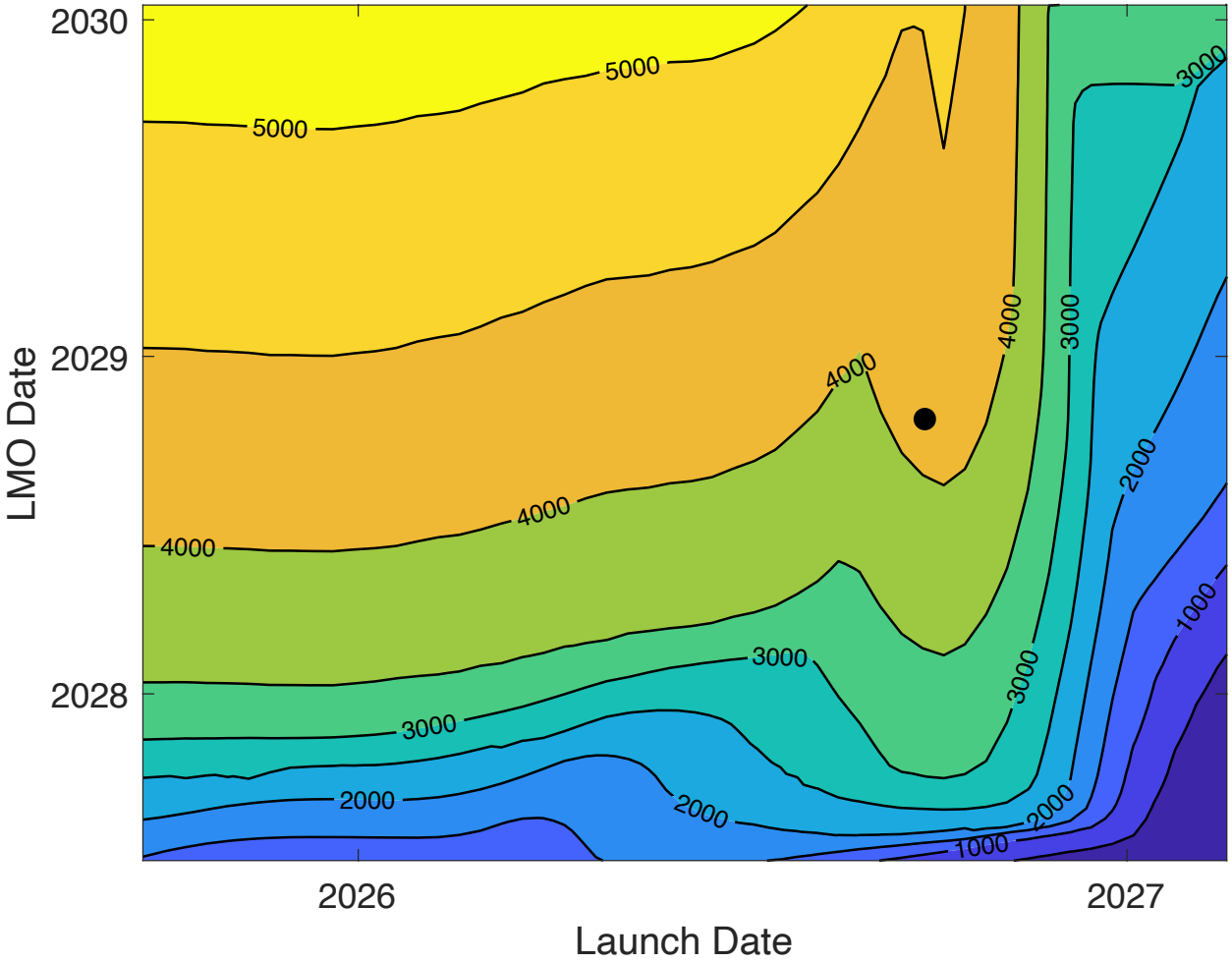

Inbound Example

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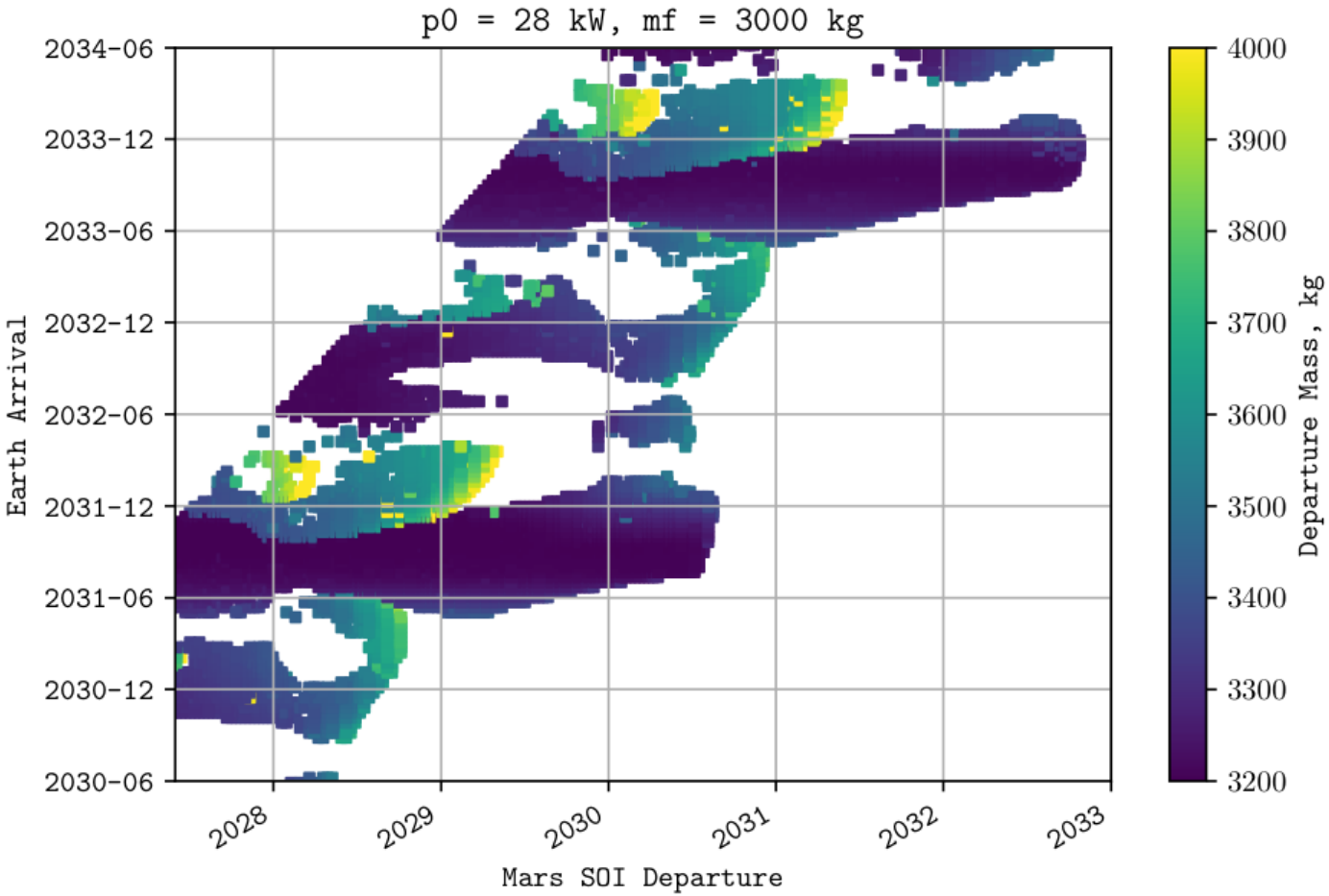

Conclusion

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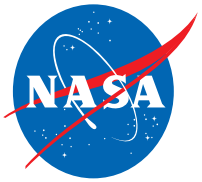
- Hybrid Chemical-SEP propulsion is well suited to the needs of an MSR Earth Return Orbiter.
- We mapped out the hybrid trajectory design space in a database.
- The trajectory database was used in conjunction with a system optimization tool to produce a matched spacecraft-trajectory pair.



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Example Grid Space

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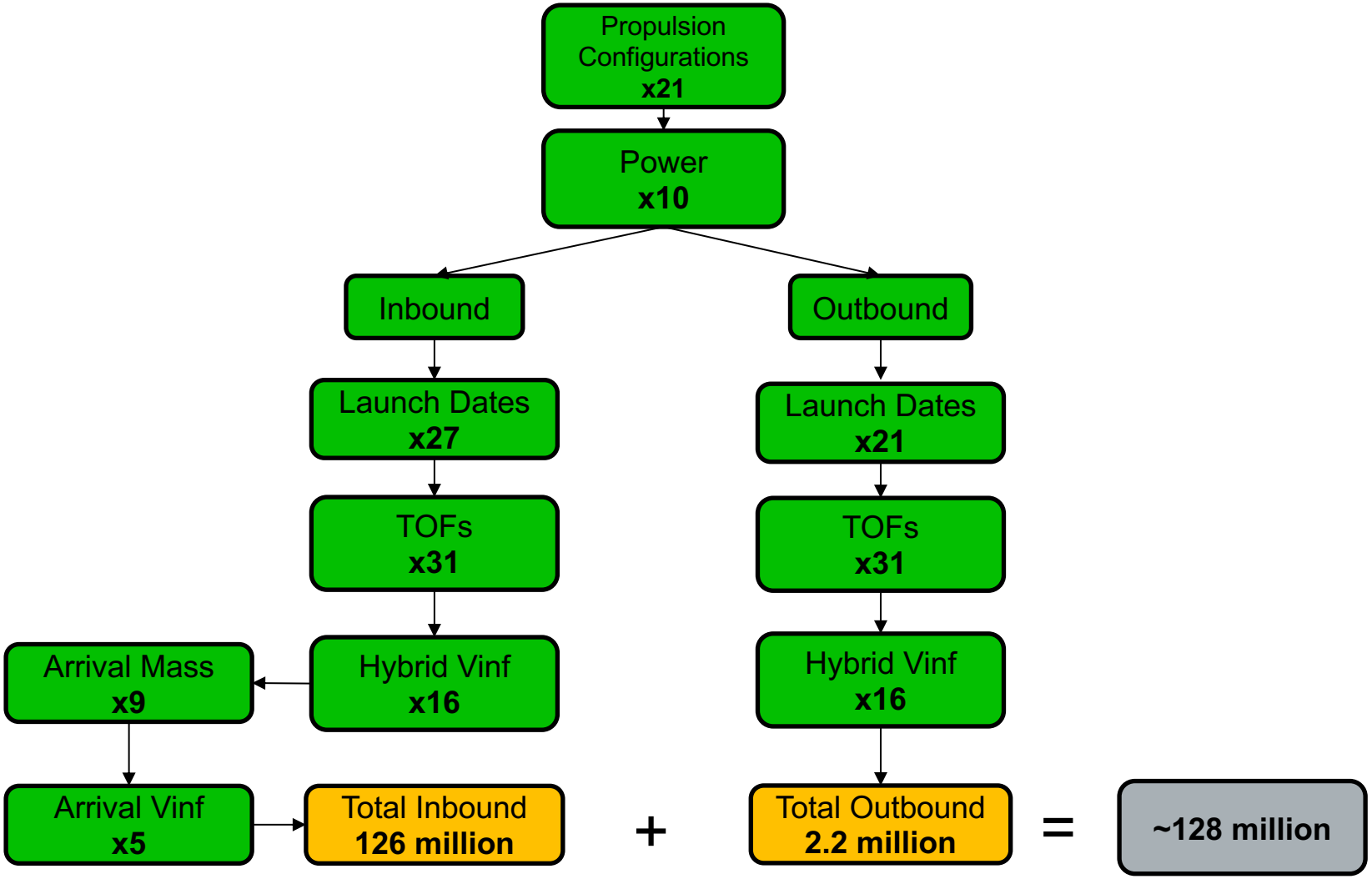

Using cluster to compute trajectories

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- Need 128 million trajectories.
- Using MALTO on parallel cluster cores, can get about 100 traps (trajectories per second).
- ~2 weeks to get through all the cases.
- Had to go through several iterations: about 400 million total trajectories and several decades of CPU time.